SPIRIT and SPECS:

Science Capabilities, Mission Concepts, and Technologies - A Progress Report

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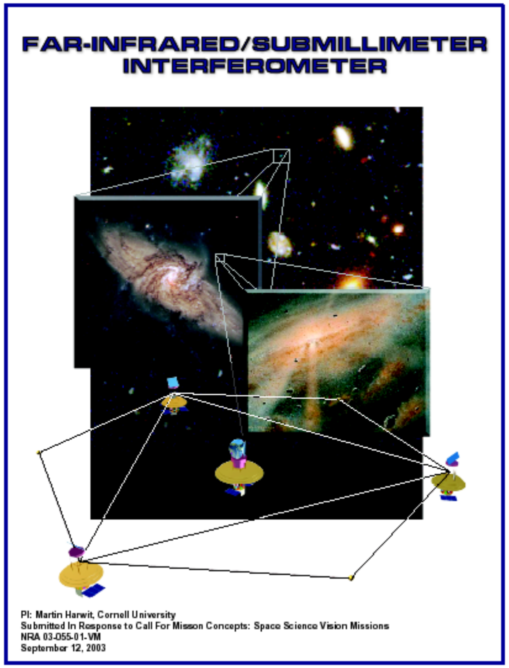
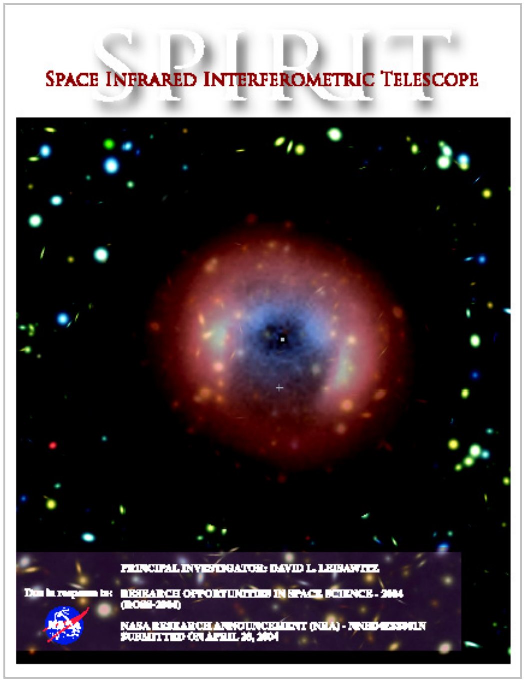
… with thanks to many members of the IR community for participating in the development of the ideas presented here

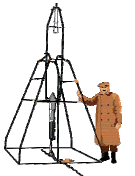
The Path Leading to SPECS

Mission Study Status

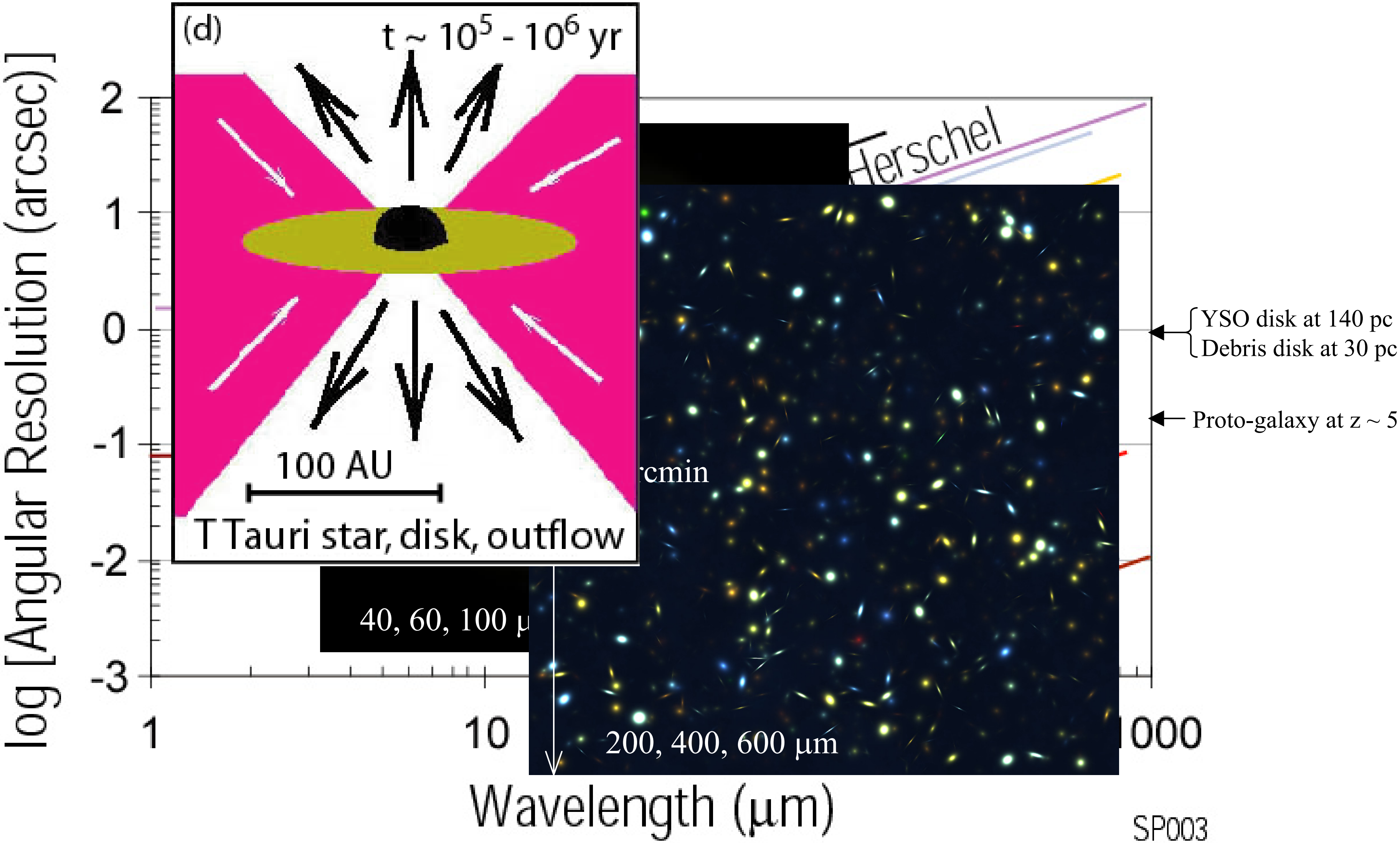
- The Infrared Era has begun
  - Spitzer now
  - Herschel soon
  - broad community and public interest
  - new information from Spitzer available for mission planning
- Key elements of the *Community Plan* are being implemented
  - SAFIR and **SPECS** Vision Mission studies underway
  - **SPIRIT** and SIRCE “Origins Probe” studies proposed, pending review
  - Reasonable progress on all technology frontiers
  - Opportunities to report to Origins and SEU Roadmap Committees coming in December



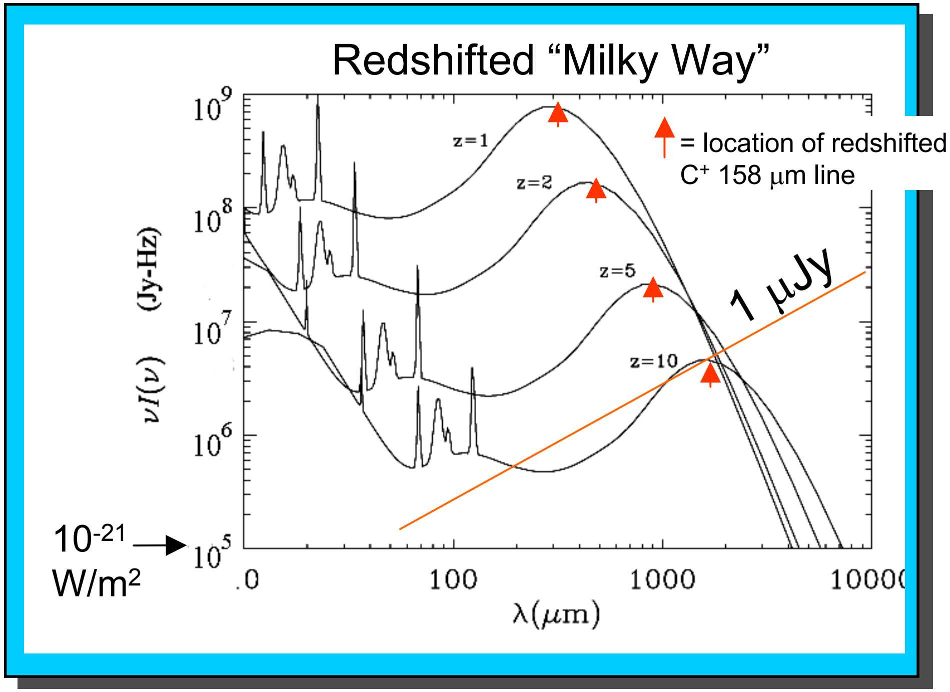


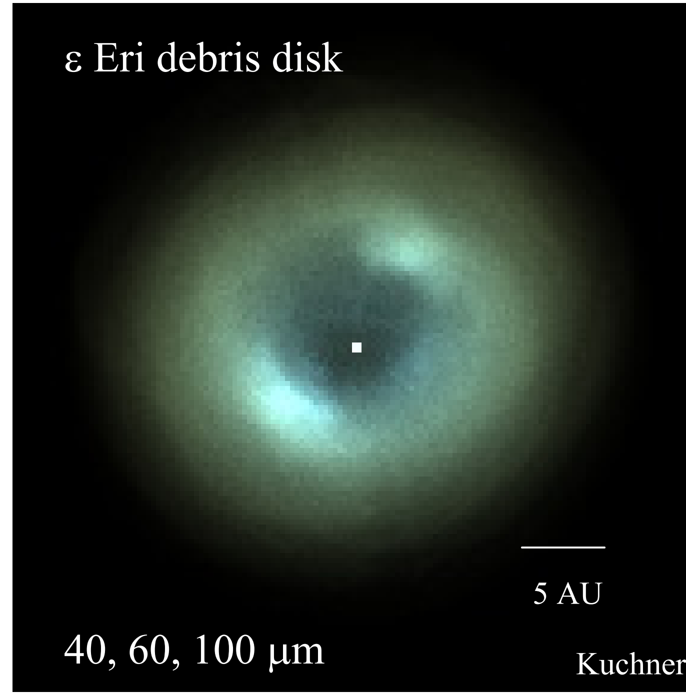


The Importance of High Angular Resolution



Sensitivity Requirements: Distant and Local





To see an L* galaxy at high z, need better than 1 μJy sensitivity. Protogalaxies might have been ~100x fainter.

To image debris disk dust emission on a 1 AU scale, need ~1 μJy sensitivity.

Why Interferometry?

An interferometer is a good design choice when angular resolution rather than sensitivity drives the aperture size requirement

Spatial resolution:

$\Delta\theta$ = 10 mas (λ / 100 μm)(b_{max} / 1 km)$^{-1}$

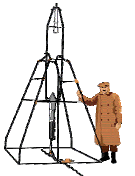
for maximum baseline b_{max} at wavelength λ. (For comparison, a diffraction limited 10 m telescope provides 2.5 arcsec resolution at 100 μm.)

Spectral line sensitivity for an unresolved (point) source:

MDLF ~ 7×10^{-22} W/m^2 $\{FBW\ I_{\nu,\,bg}(MJy/sr)/[n(n-1)(\tau_{sys}/0.1)]\}^{1/2}(D/4m)^{-2}(t/10^5 s)^{-1/2}$

for n = 3 mirrors of diameter D in integration time t, where τ_{sys} is the system efficiency and FBW, the fractional bandwidth, could be ~0.7.

In the far-IR/sub-mm, a total light collecting area comparable to that of JWST provides adequate sensitivity, but an effective aperture diameter (b_{max}) of ~30 - 50 m is needed to overcome extragalactic source confusion into the sub-mm, 1 km to provide HST (or JWST) class angular resolution.



Far-IR Diagnostic Potential

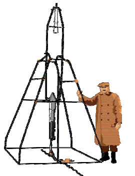
Spectroscopy is vital to our ability to answer the important science questions.

For extragalactic problems we might be satisfied to measure the integrated line intensity. R ~ 1000 would be okay.

However, for star formation research we are interested in resolving lines. For this we desire R > 10^5.

Typical Spectral Lines[1]	Derived Properties
Starburst Galaxies	
[ArIII]**9**/[ArII]**7**,[NeIII]**15**/[NeII]**12**, [NIII]**57**, [NII]**122**	Ionizing SED[2], U[3], IMF[4], age
H recombination lines	Age, IMF, starburst luminosity
Dust features	Starburst luminosity
Active Galactic Nuclei (AGN)	
[NeV]**14**,**24**/[NeIII]**15**, [OIV]**25**, [SiIX]**4**	U, SED
Broad H recombination lines	Buried AGN
Dust features	AGN luminosity
Interstellar Medium (ISM)	
HII Regions	
[NeIII]**36**/[NeIII]**15**, [SIII]**34**/[SIII]**19**, [OIII]**52**/[OIII]**88**	Visual extinction (A_V), electron density (n_e)
All Ne lines, H recombination	Abundance
AGN Narrow Line Region (NLR)	
[NeV]**14/24**, [NeIII]**36/15**	A_V(NLR), n_e
Photon Dominated Regions, Shocks	
H_2 **2**, [S I]**25**, [SiII]**35**, PAH[6] features, [CII]**158**, [OI] **63**,**145**, [FeII]**18**,**24**,[FeIII]**24**	Far-UV field strength & SED, density, temperature, shock parameters
Molecular Clouds, Protostars, and Disks	
Rotational and rovibrational lines of H_2O, CO, and small hydrides	Temperature, density, turbulent & systemic velocities, isotopic abundances

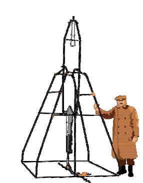
[1] Rest wavelengths in μm, but redshifted at high z
[2] Spectral Energy Distribution
[3] Ionization parameter
[4] Initial Mass Function



SPECS Design Reference Mission

Author	fov arcsec	Number of fields	Ang. Resln mas	Wavelength Range mu	Spectral Resln.	Sensitivity muJy	Dynamic Range
Blain 1	100	10	1000	40 - 500 mu	R ~ 100	10^{-3}	
Blain 2	100	1000	100	500 mu	R ~ 100	1 to 10^3	
Blain 3	10	1000	10	40- 500 mu	R=10-100	10^3	
Lawrence	4	100	10 @ 50mu	full range		10^3	
Satyapal	2	100?	50	45-75 mu	R = 10^3	3	
Mundy	4	10?			R = 5	10	~1000
Leisawitz1	20	~ 200	10@40mu	40-160	R = 5	2x10^{-2}	~1000
Calzetti	60	300	50	40-800	R = 20	10^{-1}	~10^4
Neufeld 1	60		100	31-560	R=10^3-10^5	3	
Neufeld 2	4		10	31-560	R=1000	3	
Neufeld 3	1	20	10	31-560	R>1000	3	1000
Harwit	5	10	50	40-800	R = 3x10^5	10^3	100
Leisawitz2	60	20	60	60-350	R = 3000-30,000	0.1	~1000

Blain 1	Ultradeep cosmological H_2 and continuum survey
Blain 2	Resolve radiation from star forming galaxies z = 1 – 5
Blain 3	ULIRGs, high red shift line and continuum radiation
Lawrence	AGNs continuum and spectral lines of host galaxies
Satyapal	Galaxy Nuclei z ~3 spectroscopy
Mundy	Protosstellar and young stellar disks and their gaps
Leisawitz 1	Structure in debris disks, dust continuum
Harwit	AGB star outflows
Calzetti	Galaxies z ~ 2 – 6.5
Neufeld 1	Water in Carbon stars
Neufeld 2	Water in Young Stellar Object disks
Neufeld 3	AGNs
Leisawitz 2	Nearby galaxies



SPECS Design Reference Mission

Wavelength range:
- Required: 40 - 600 μm
- Desirable: 30 - 800 μm

Angular Resolution:
- 10 mas at 40 μm
- 50 mas at 200 μm

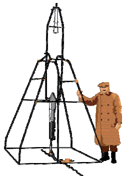
Field of view:
- Required 60 arcsec
- Desirable: 100 arcsec

Field or Regard:
- Minimum +/- 20 degrees off ecliptic plane
- A larger field is desirable

Photometry:
- Spectral Resolution R = 3
- Sensitivity 10^{-1} μJy
- Dynamic Range: 10^4

Low resolution Spectroscopy:
- $R = 10^3$
- Sensitivity 10^{-1} μJy
- Dynamic Range 10^3

High resolution Spectroscopy:
- Required: $R = 10^5$
- Desirable: $R = 3 \times 10^5$
- Sensitivity 3 μJy



“Flow Down” from Science Questions to Technology Requirements

SPECS Requirements Flow Down

Science Goals

Characterize the epoch of first generation star formation

Probe the luminosity evolution and physical conditions in galaxies since the epoch at which they formed

Observe the chemical and dynamical processes that lead to the formation of stars

Image the dusty disks around newly formed stars to study temperature, density, grain size distribution and chemical fractionation to learn how planetary systems form

→

Measurement Capabilities

Far-IR and Submillimeter Imaging and Spectroscopy

Spectral Range
~40 - 800 μm

Angular Resolution
0.05 (λ / 250 μm) arcsec

Spectral Resolution
$\lambda/\Delta\lambda = 1000$ for galaxies and 10^5 for protostars

Field of View
1’ required, 4’ desired

Sensitivity
10^{-21} W m^{-2} in 10^5 sec for continuum and 10^{-22} W m^{-2} for spectral lines

Observations
At least one target a day

→

Engineering Implications

System Angular Resolution, Metrology and Performance
- Baselines adjustable up to 1 km
- 2 or 3 light collectors plus Michelson beam combiner and spectrometer
- 3 - 10 m diameter collector mirrors
- 4 K optics
- 0.5 μm mirror surface
- Metrology to ~1 μm
- sub-arcsecond relative pointing

- **Detectors**
- NEP < 10^{-20} W Hz$^{-1/2}$
- 50 x 50 pixel array

- **Orientation**
- Able to view at least +/-20^{o} from ecliptic

→

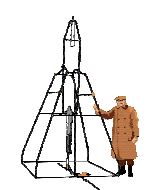
Key Technologies

Submillimeter detectors
- FIR photon counters (40 - 800 μm)
- Superconducting multiplexers

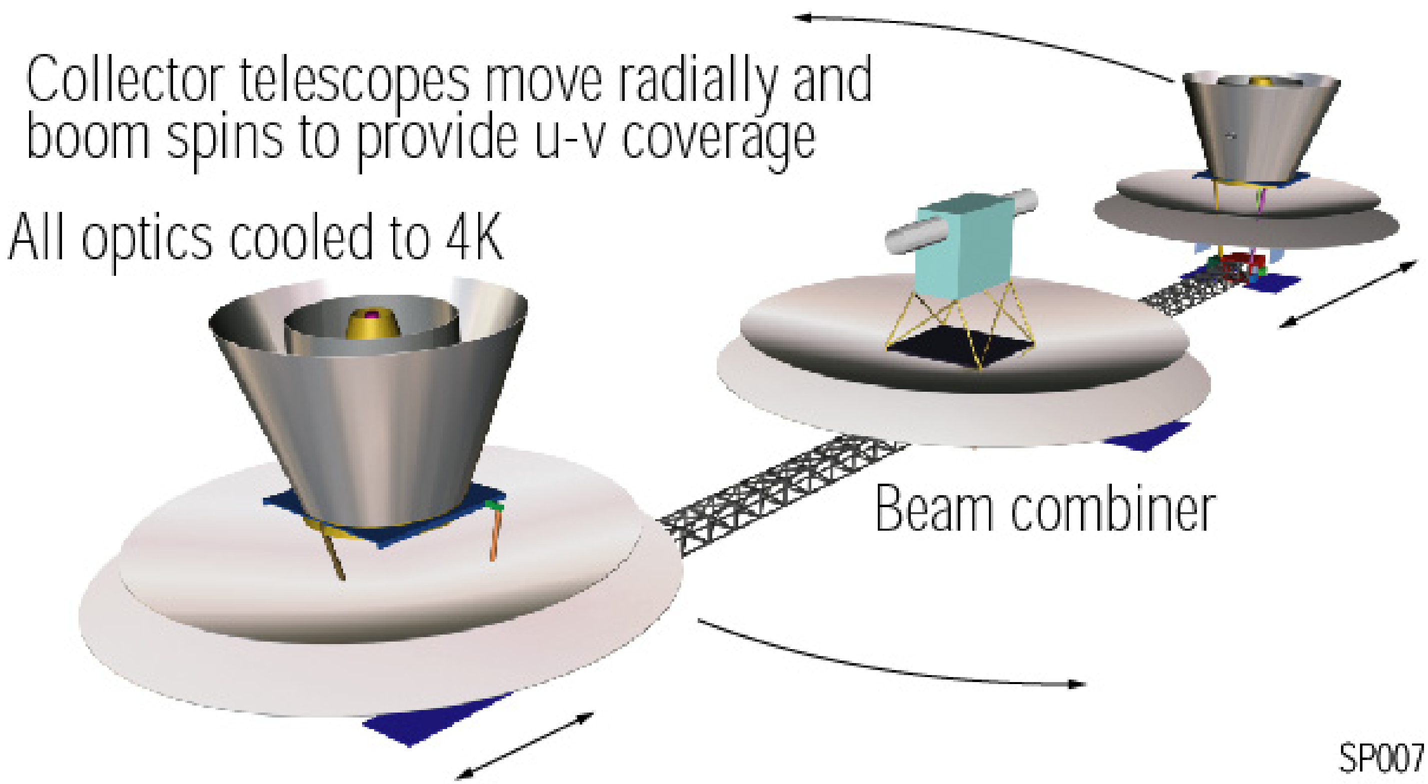
Active and passive cooling
- 0.1 K coolers
- Mechanical coolers
- 4K cooling loops
- Deployable multi-layer sunshields

Formation flying
- Tethers in spin-stabilized formation
- Inertial referencing for phasing, guiding

Optics and interferometry
- Lightweight 4K optics (3 - 10 m)
- Wide-field imaging interferometry
- Cryogenic delay line



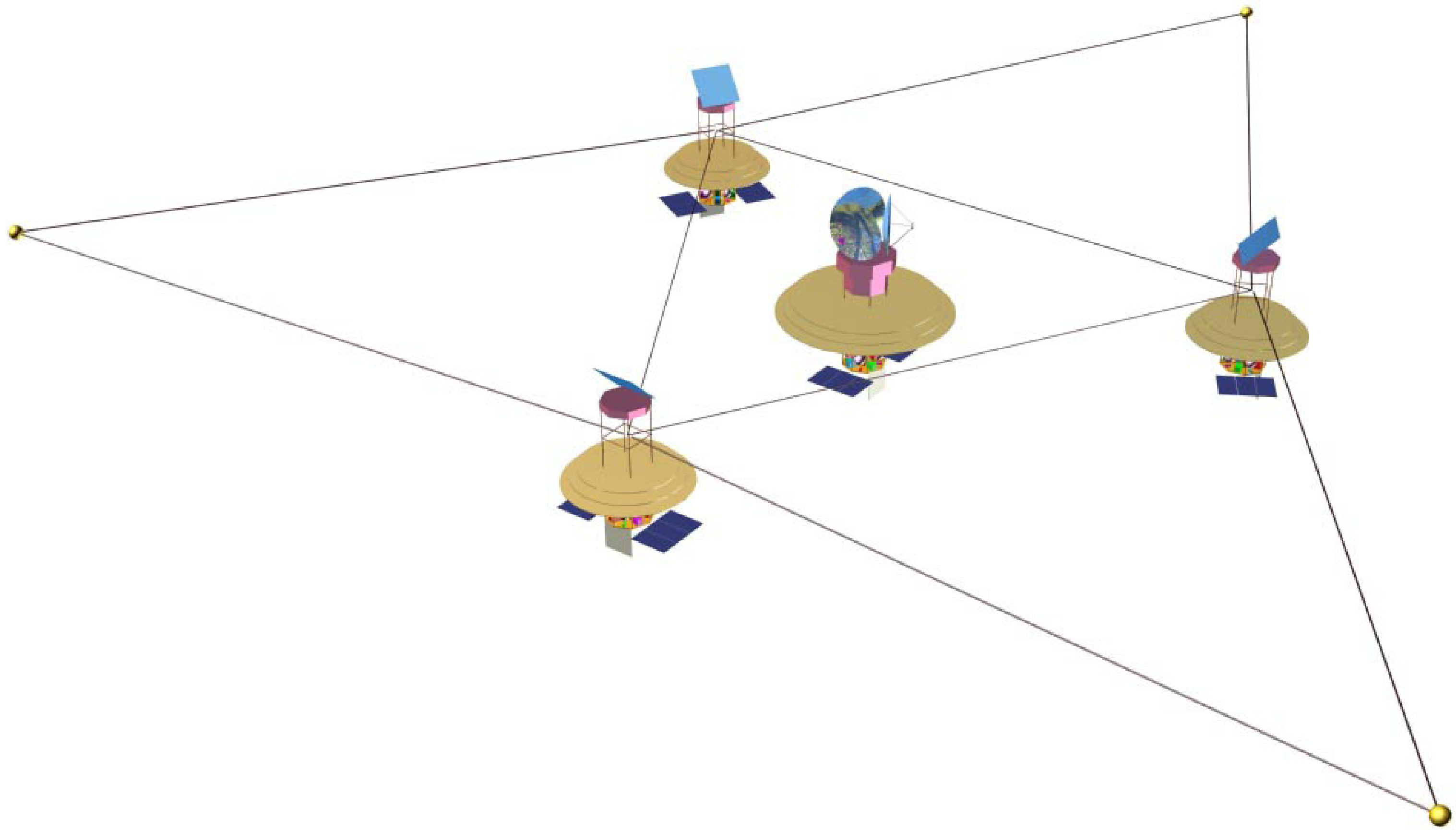
SPIRIT Mission Concept



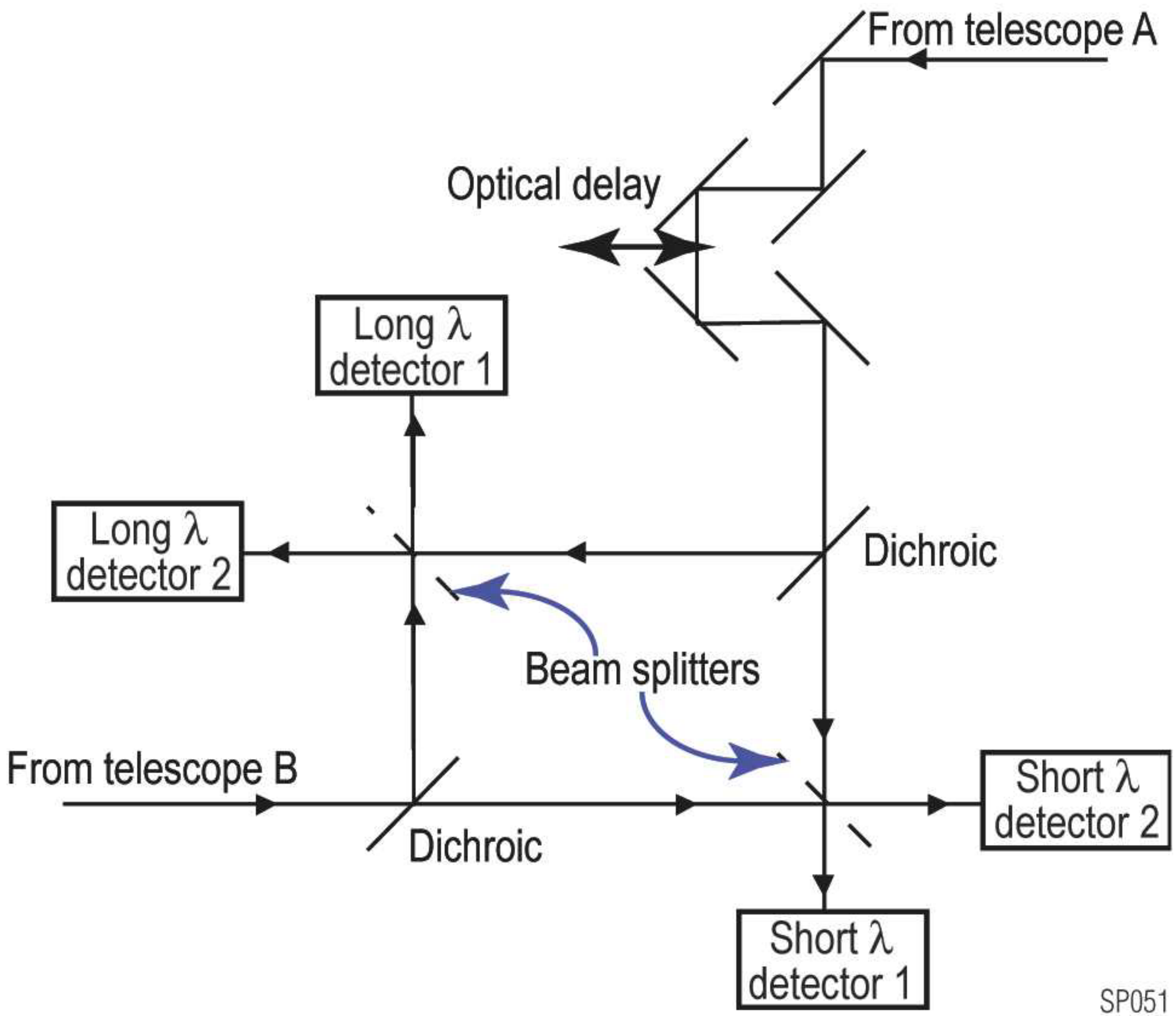
SPIRIT could fly in the next decade as an Origins Probe

SPECS Mission Concept

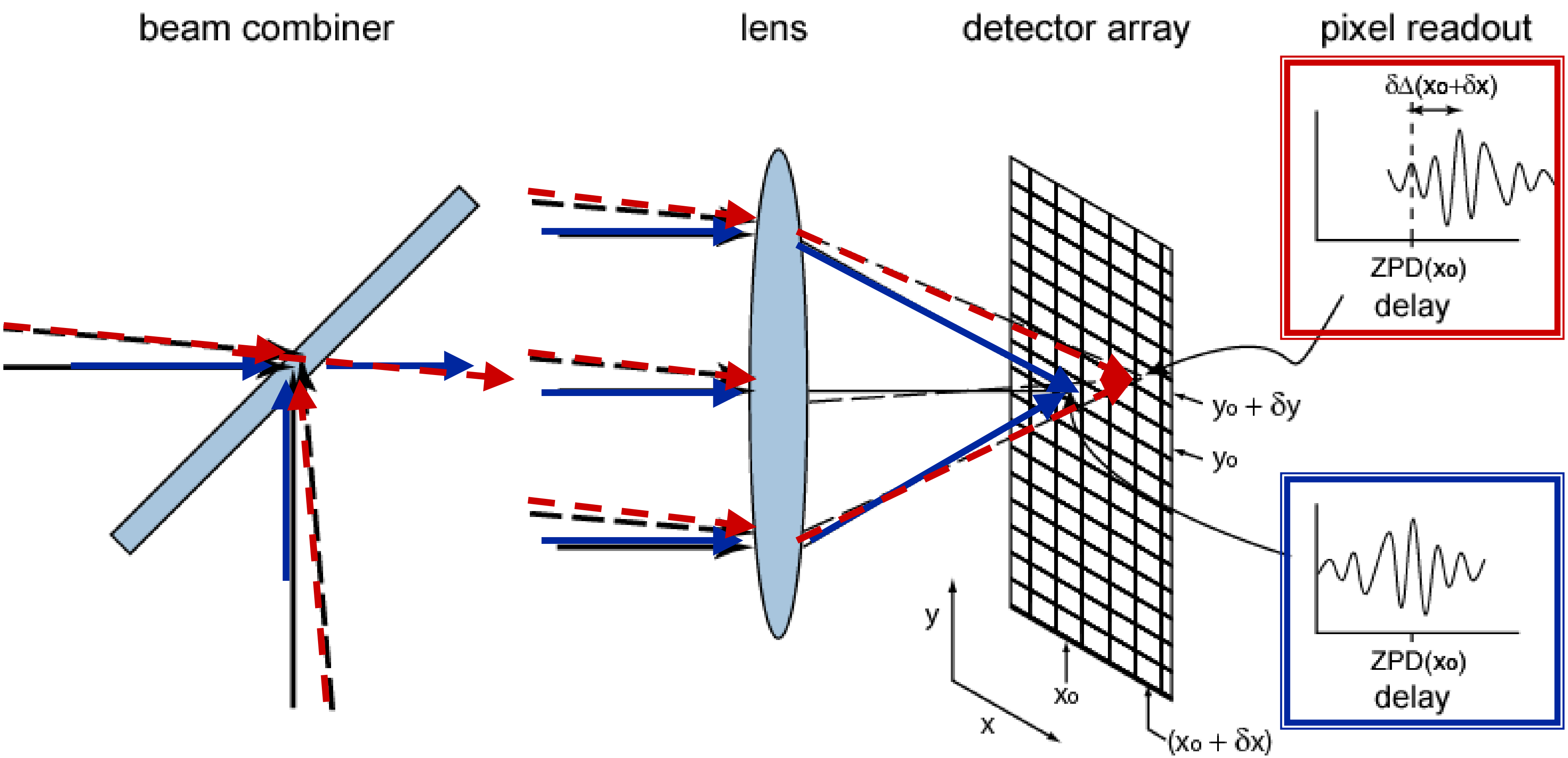
Partially contracted array



Beam Combiner Concept

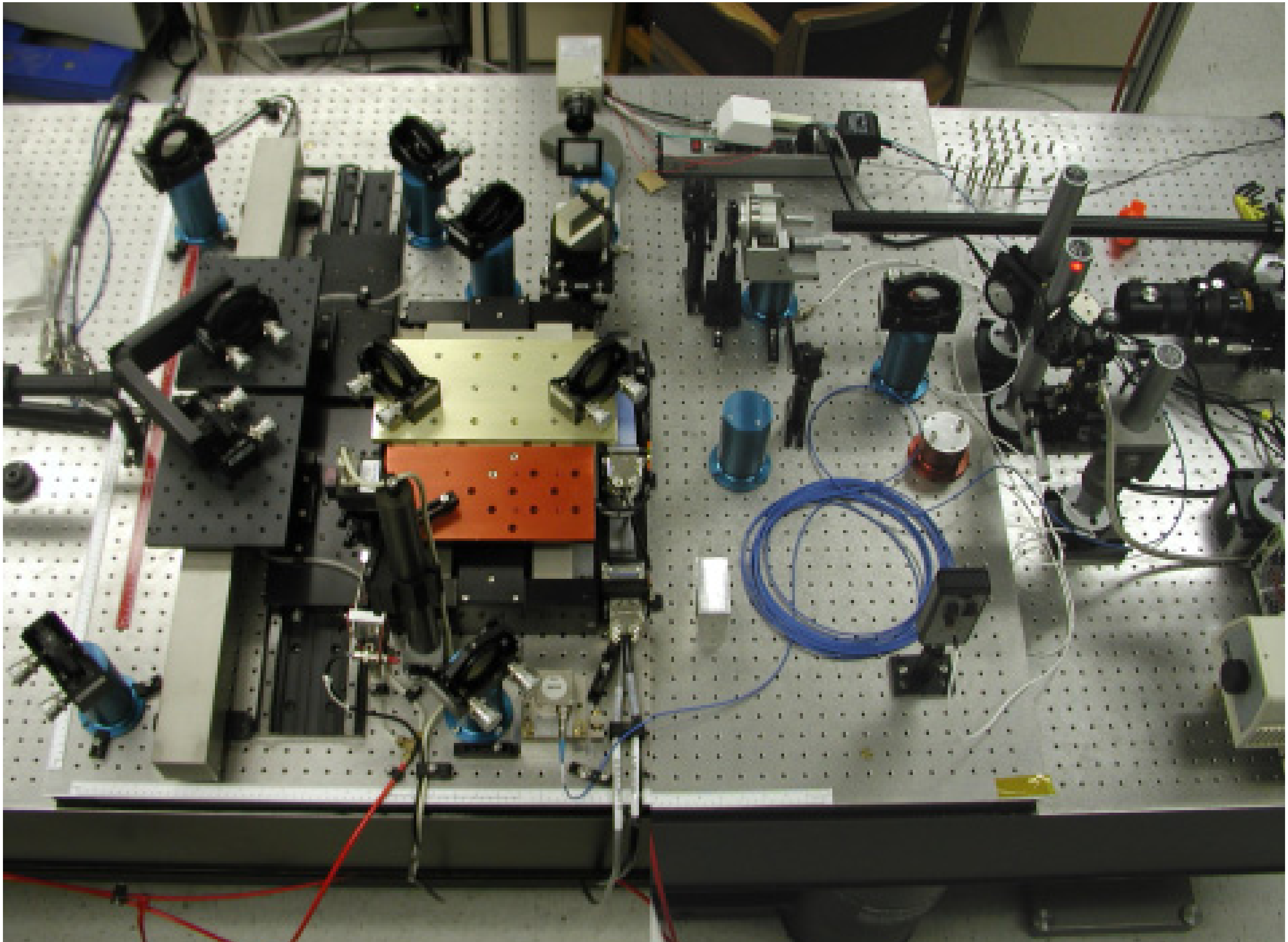


How does it work?

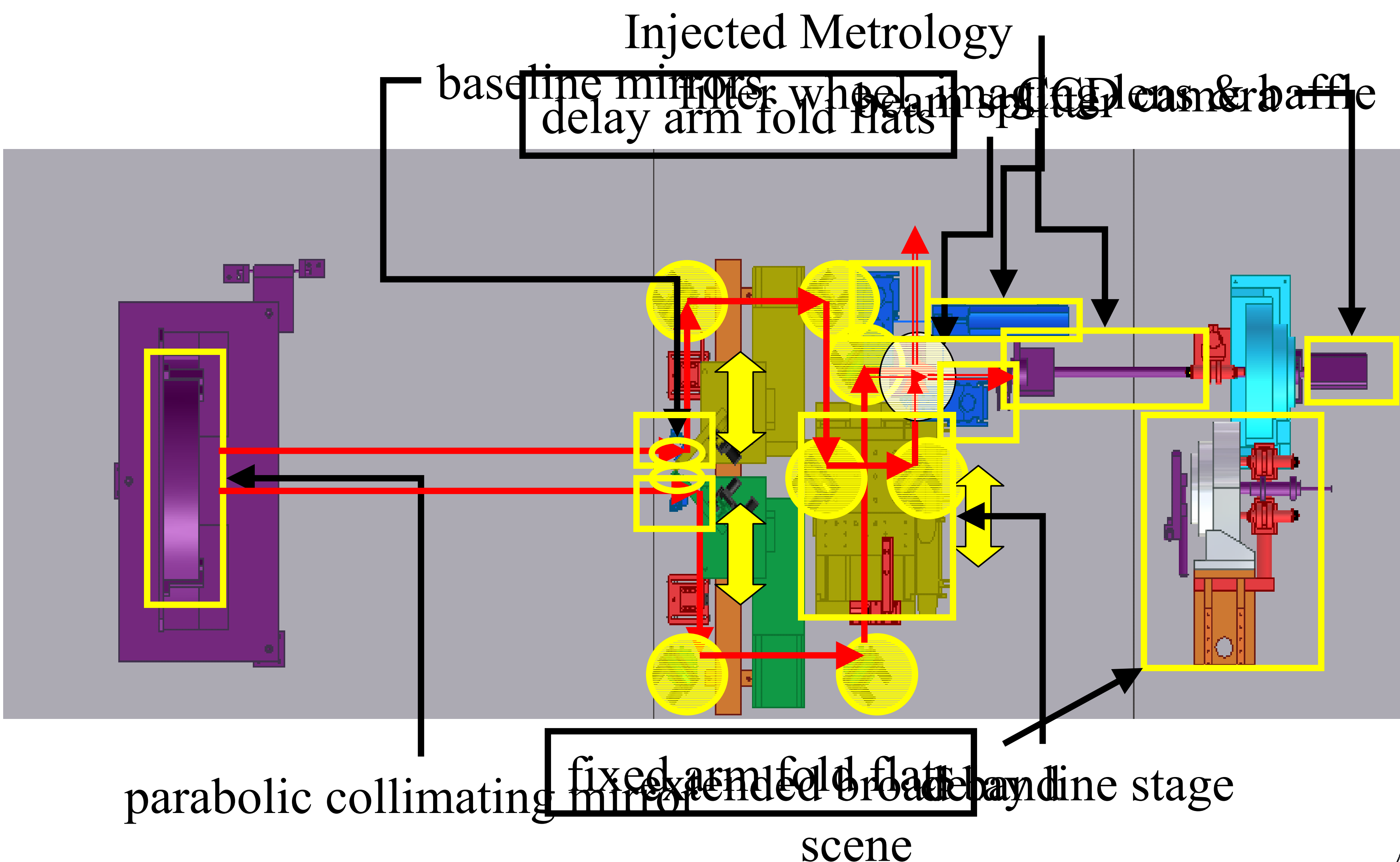


$$\theta_{FOV} \approx 1.7 \text{ arcmin } (N_{pix}/32)\ (\lambda/100\ \mu m)\ (d\ /4\ m)^{-1}$$

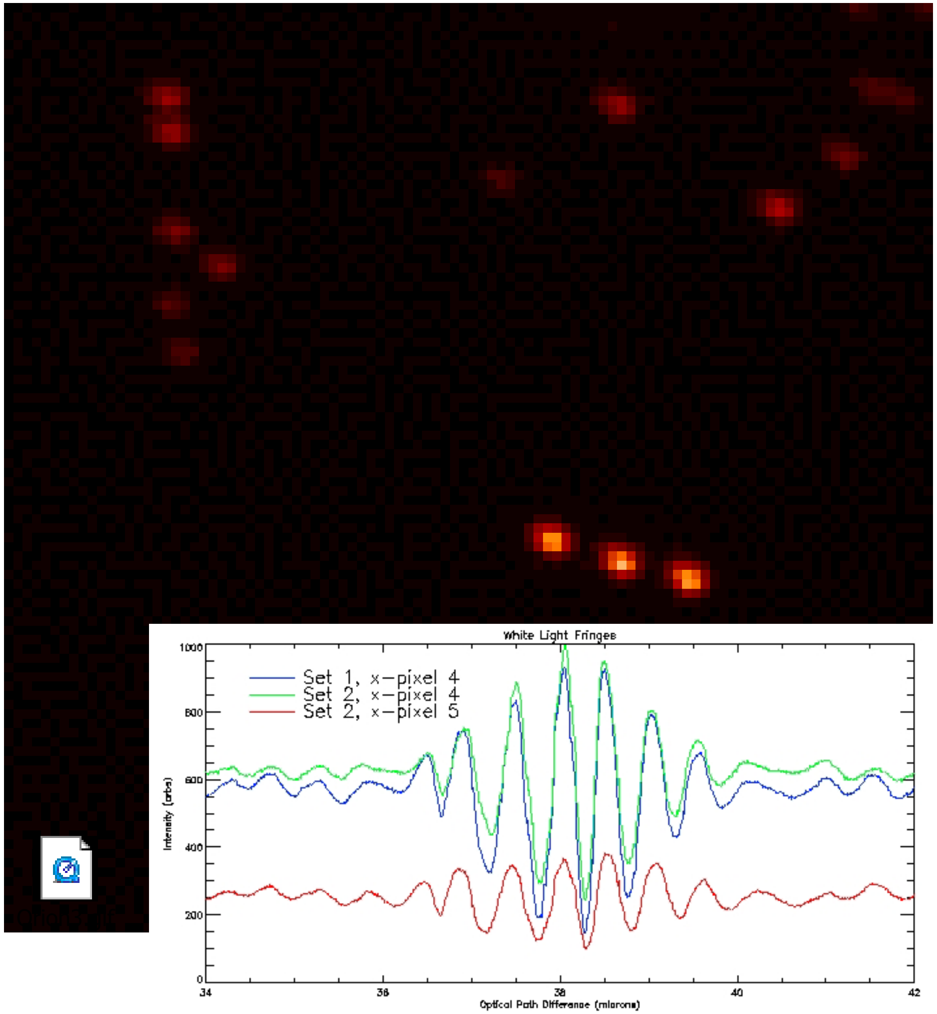
Wide-field Imaging Interferometry Testbed (WIIT)



WIIT Schematic - Plan View

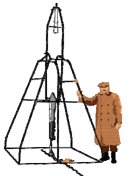


A Simple Demonstration of Wide-field Double Fourier Interferometry

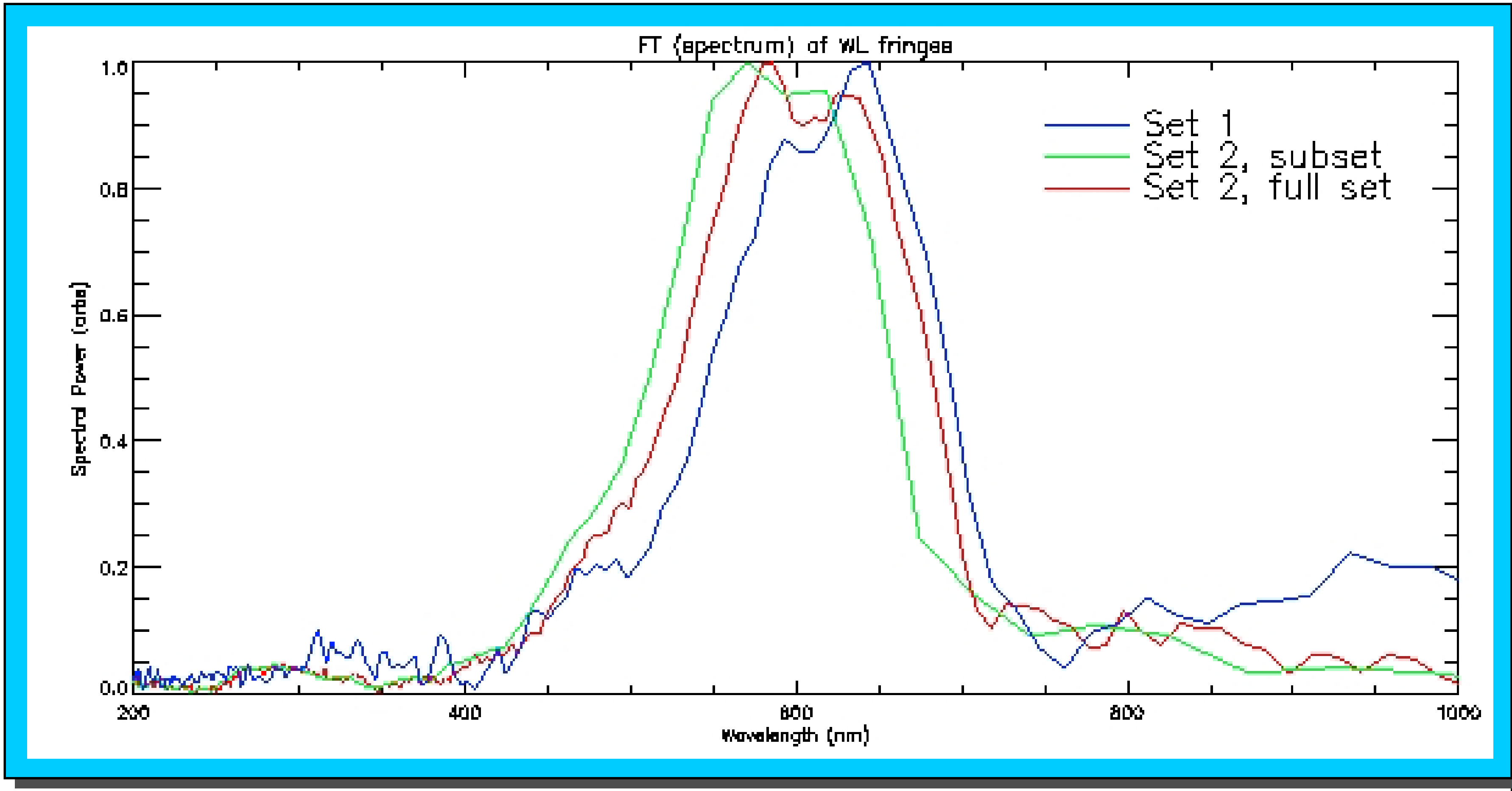


White light sources separated by >>λ/d appear in different camera pixels. As the optical delay line is scanned, a flickering signal is seen in different pixels as the white light fringes from the corresponding sources approach the zero path difference point.

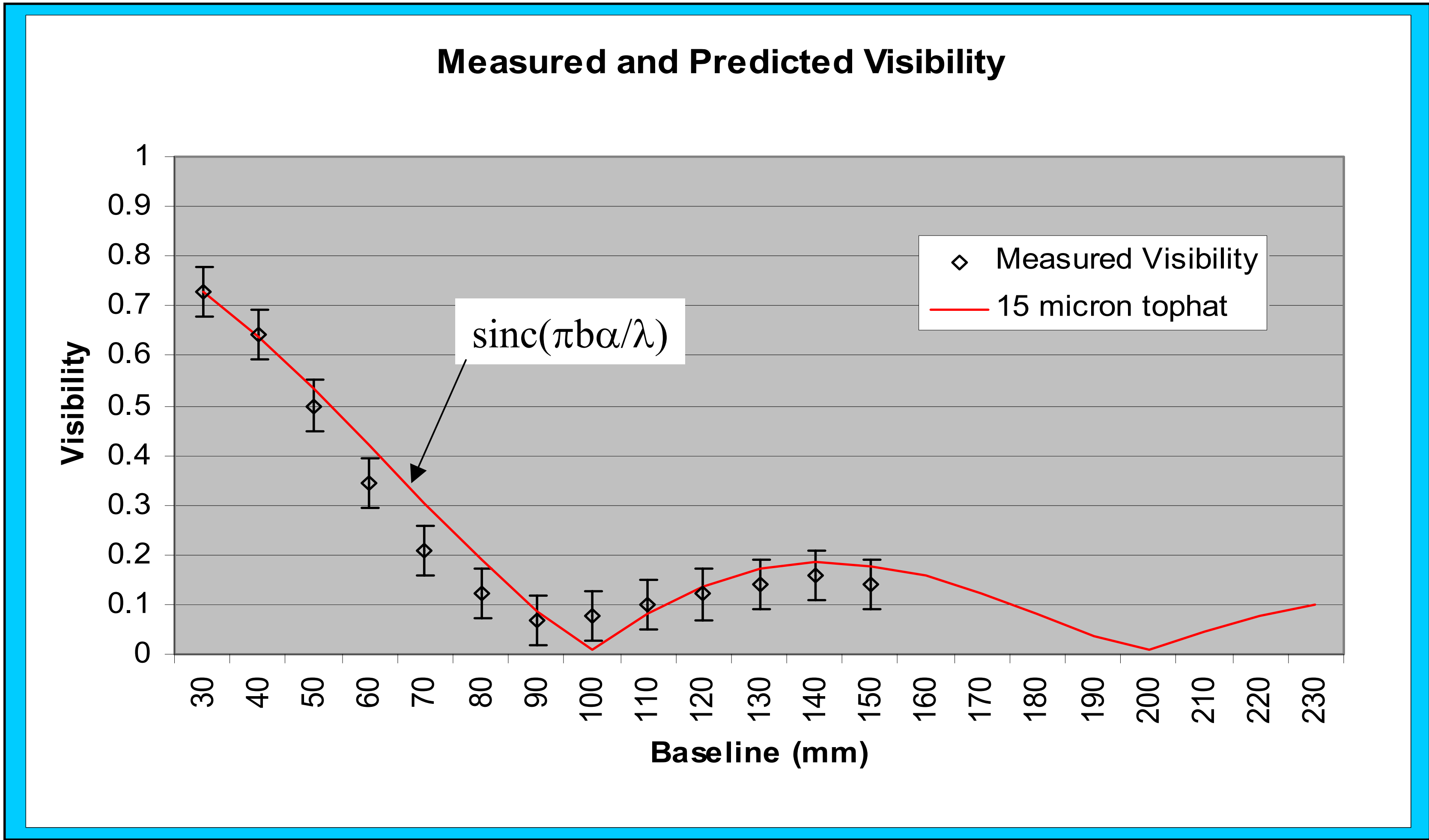
A different white light interferogram is recorded in each pixel



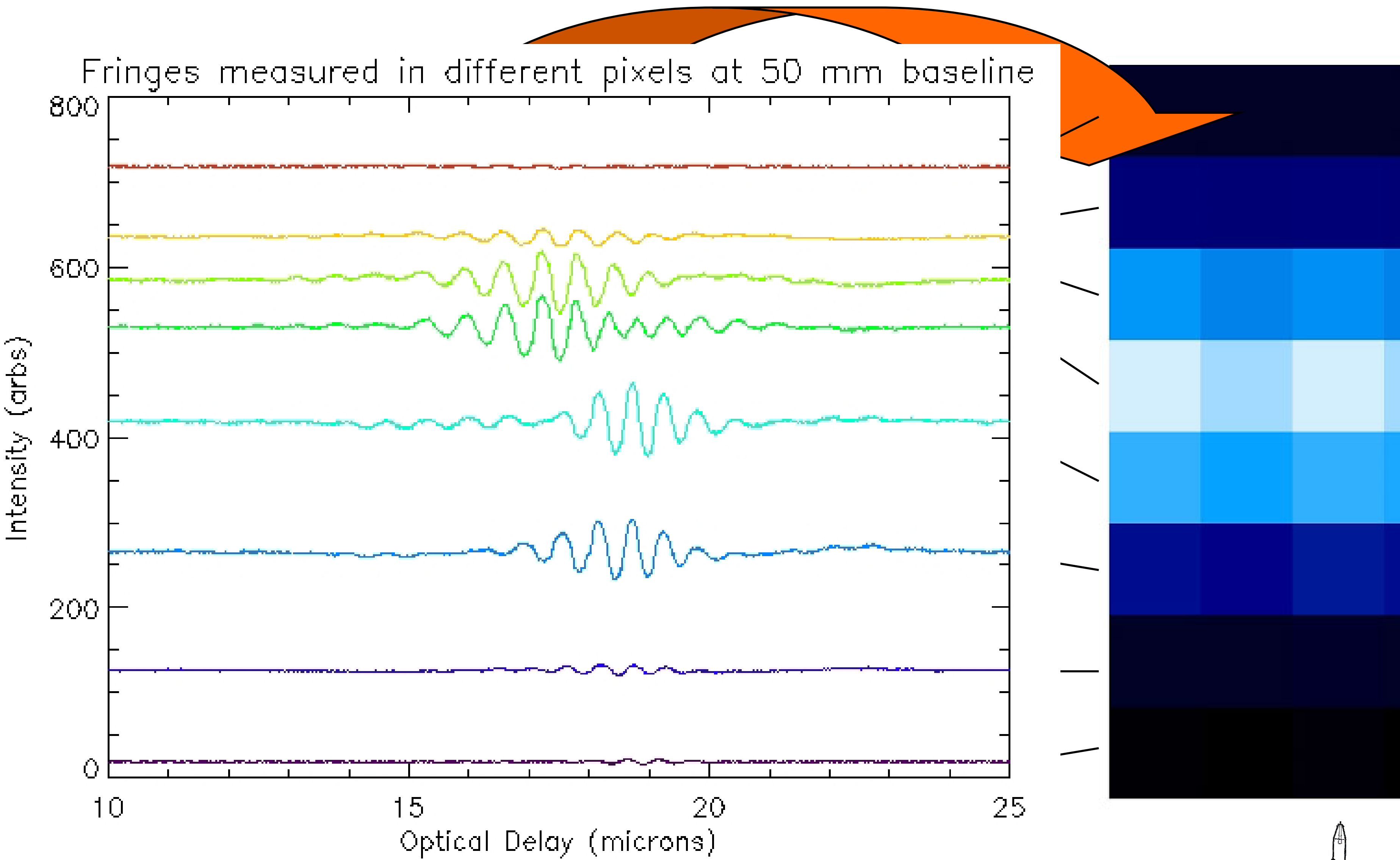
The Spectrum of Each Source is the Fourier Transform of its White Light Interferogram



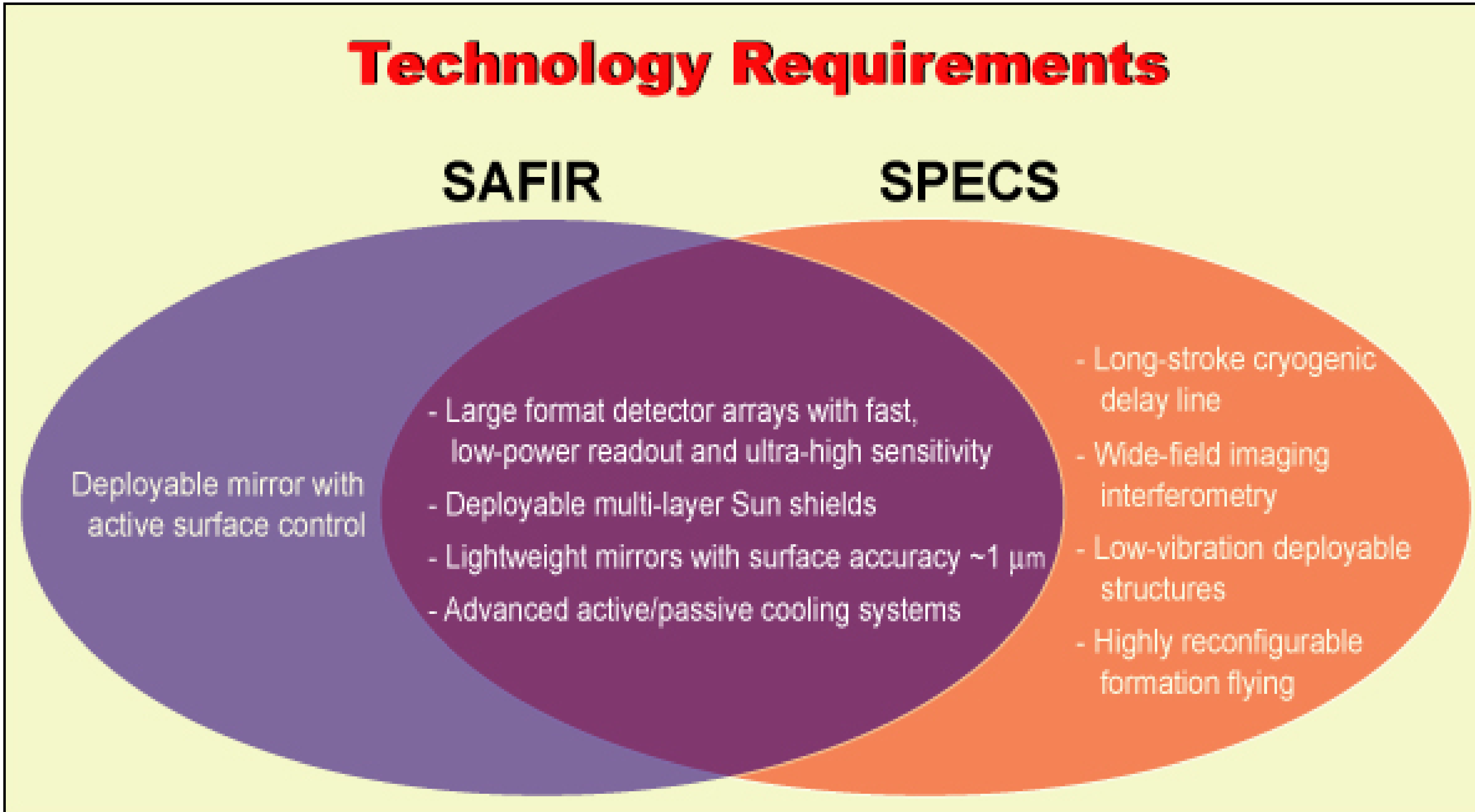
Spatial Interferometry (Imaging)

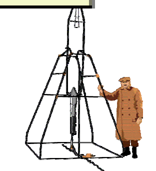


Wide-field Imaging Interferometry Data



Technology: Heritage and Common Needs

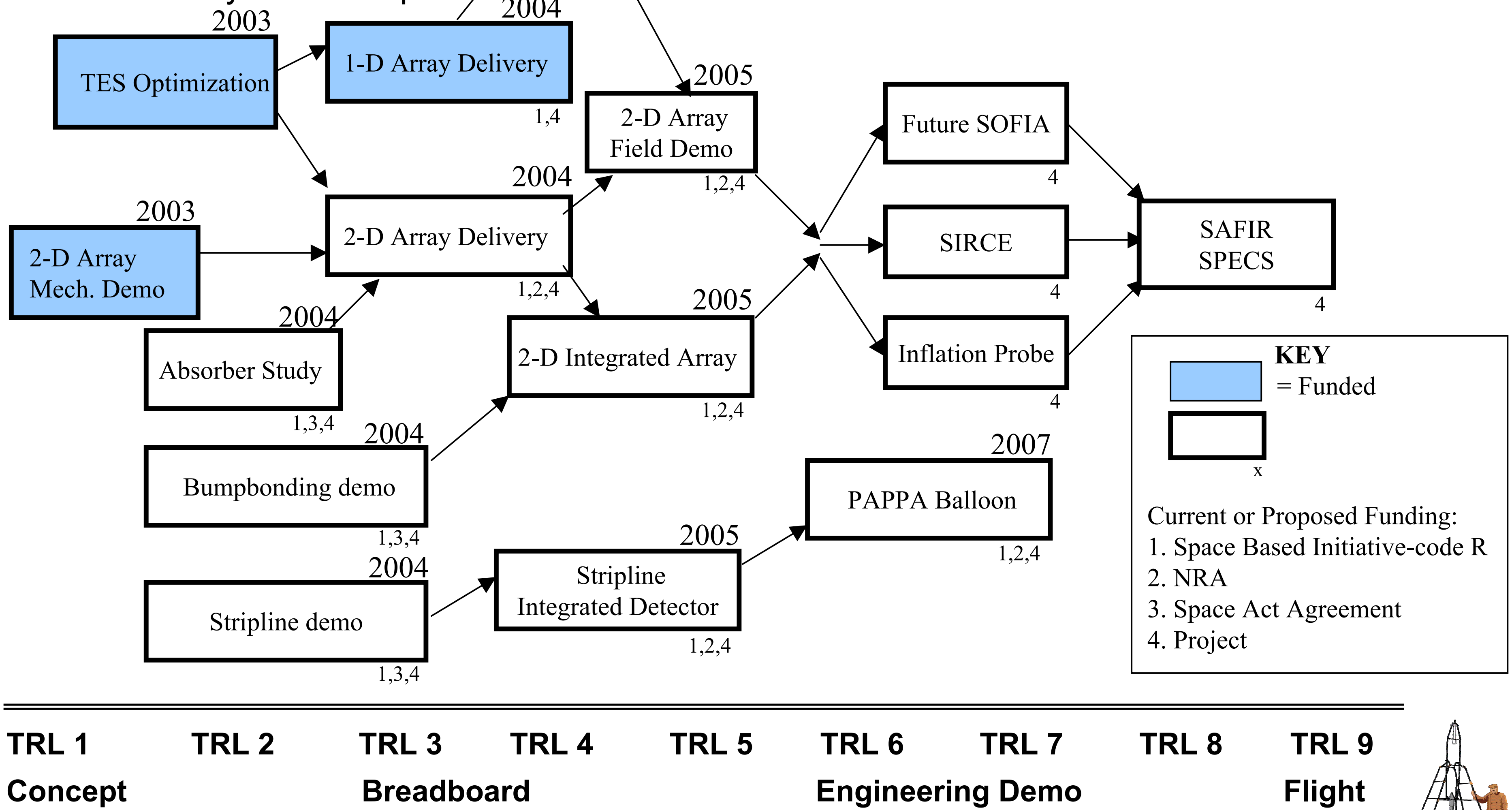




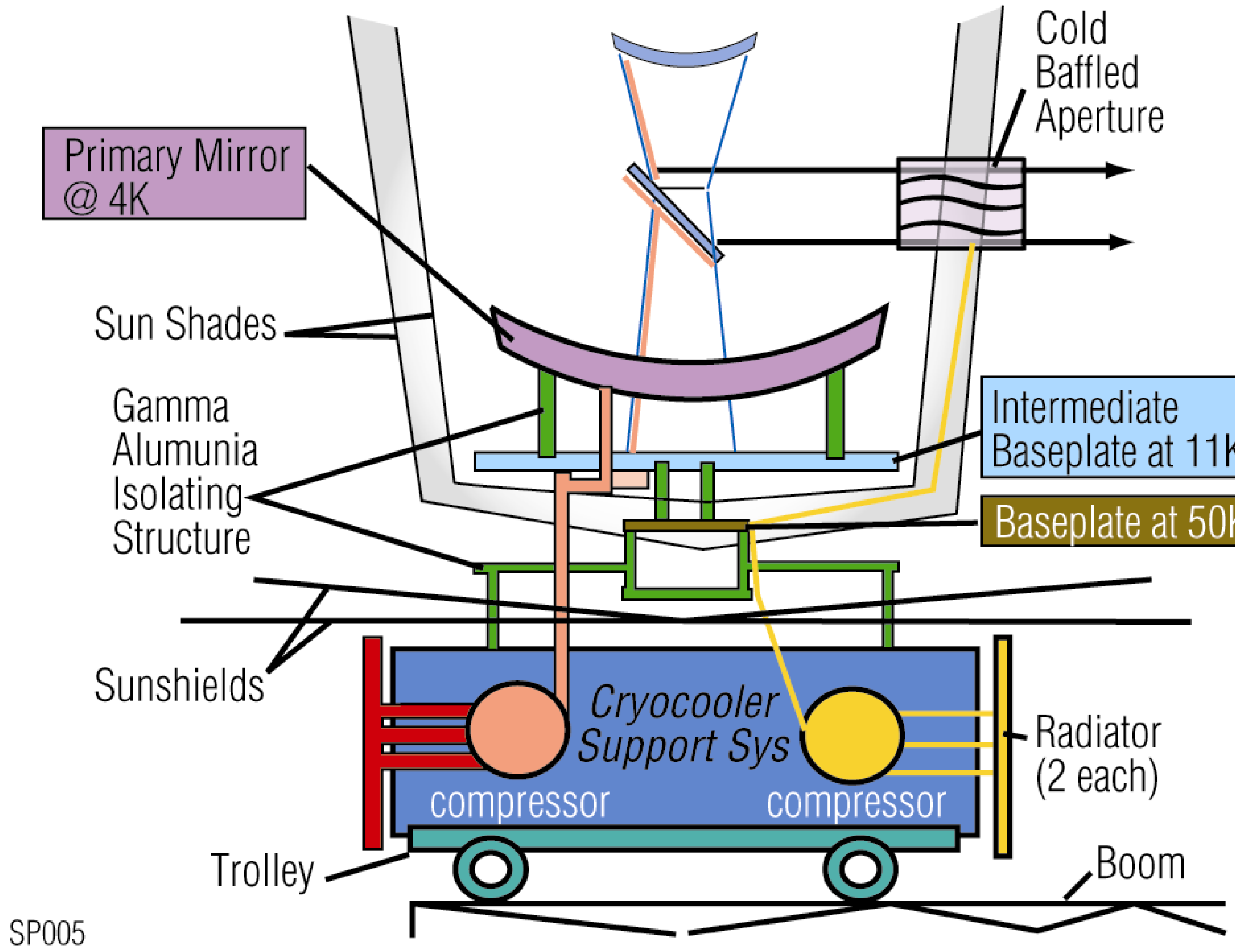
Detector Roadmap

Critical Technologies for Flight-worthy High Sensitivity Far-Infrared Detector Arrays Roadmap

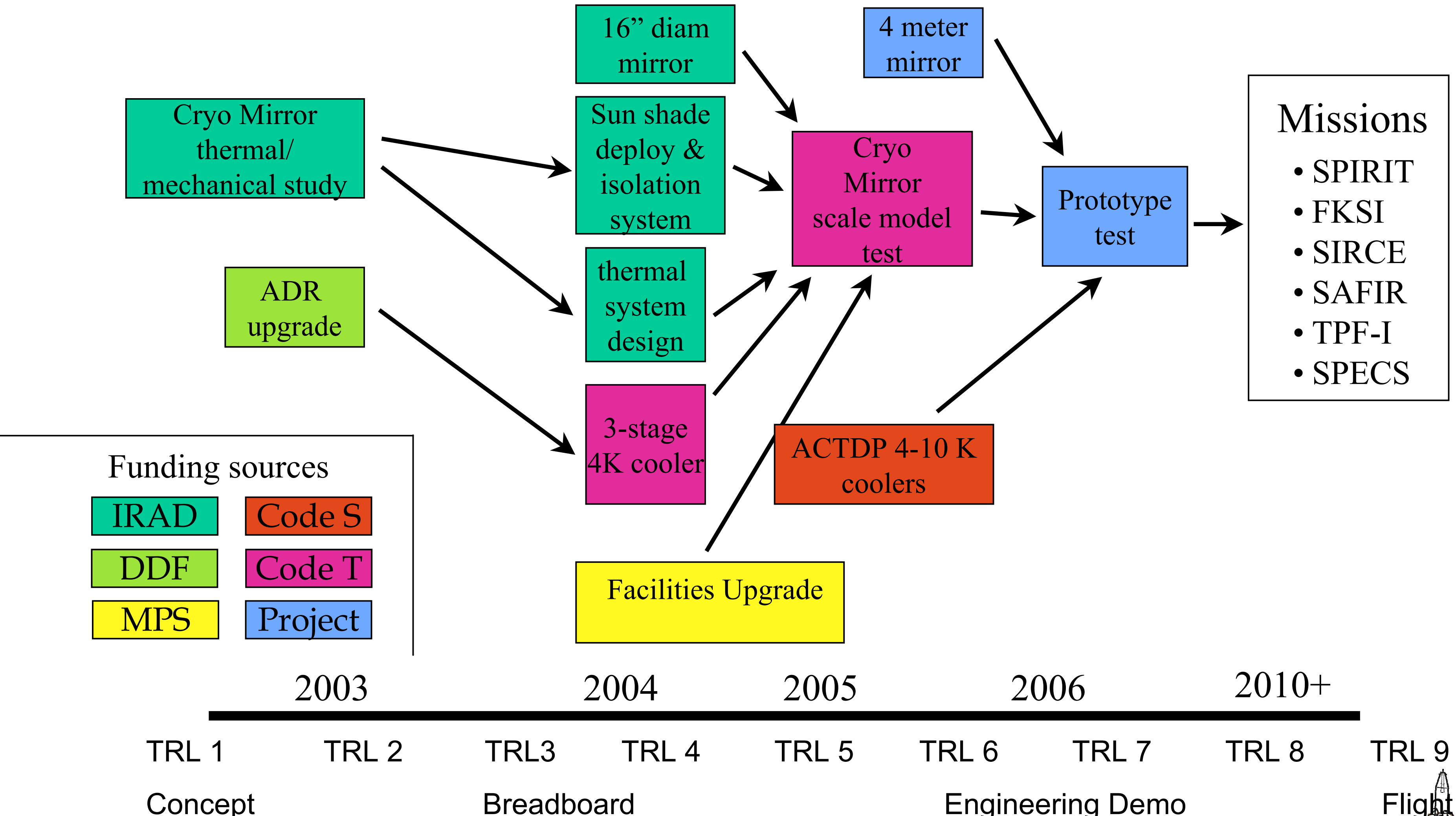
Also see:
http://www.sofia.usra.edu/det_workshop/report/ISMDWG_final.pdf



Cooling Large Mirrors



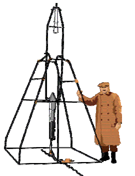
Cryo-optics Roadmap



Wide-field Imaging Roadmap

- Produce high-quality data sets (full u-v plane coverage, spatially and spectrally complex scenes)
- Develop and validate a high-fidelity, end-to-end model of the Wide-field Imaging Interferometry Testbed (WIIT)
- Automate WIIT to simulate on-the-fly observing
- Improve the testbed environment; operate in the Diffracton Grating Evaluation Facility
- Develop and evaluate algorithms for wide-field imaging interferometry

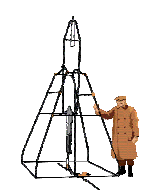
This plan results in advancement of the Technology Readiness Level from TRL 3 to TRL 5 during the next three years.



Delay Line Roadmap

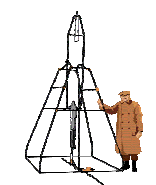
Instrument name	Architecture	Life (number of strokes)	Temperature	Optical Stroke	Physical Stroke	Diameter of optics	Rate of Motion (physical)
SPIRIT requirement	To be determined (TBD)	1.6 million	4K	~1 m	TBD	TBD	~6 mm/sec
COBE FIRAS	Flex pivot suspension	1.2 million	2 K	70 mm	24 mm	10.8 x 13 cm	mm/sec
Cassini CIRS	Parallel flexure suspension	5 million	170 K	2 cm	10.4 mm	5 cm	mm/sec
Aura TES	Band drive	12 million	273 K	33.8 cm	8.4 cm	5 cm	mm/sec
TPF Prototype	PZT on stepper-motor-driven flexure	> 500,000	77 K	20 cm	10 cm	3.8 cm	3 mm/sec

- TPF prototype developed and tested at JPL
- Two alternative designs - one with rotational flexures, the other with linear flexures - under development at GSFC, intended to meet SPIRIT and SPECS requirements



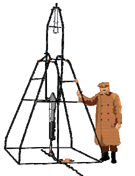
Highly Reconfigurable Arrays

- "Highly reconfigurable" for dense *u-v* plane coverage
- Rotating deployable boom with light collectors on trolleys - works for b_{max} up to ~50 m
- Formation flying without tethers works for b_{max} up to ~200 m (too much thruster propellant or too few images per mission if b_{max} bigger)
- Formation flying with tethers works for b_{max} up to ~1 km
  - CETDP-funded study (Quinn et al.) suggests viability, addresses requirements, alternative architectures, re-pointing; tools developed to facilitate further analysis
  - Lorenzini et al. have analyzed tether dynamics
  - Sell et al. Phase I SBIR contract to adapt SPHEREs to test tethers, could lead to air table demo and first space demo
  - Need inexpensive long-baseline space demo scalable to SPECS



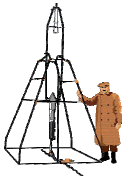
Conclusions

- Interferometry is inevitable
- Broad science capability is an asset - community buy-in and programmatic agility
- FIR/SMM imaging is easier than optical astrometry (SIM) or mid-IR nulling (TPF-I)
- Clever ideas are needed to maximize available spectral resolution and satisfy all science requirements
- SPIRIT will be ready to propose as an "Origins Probe" as soon as an AO comes out - "new initiative" needed
- Spitzer and Herschel will light the torch

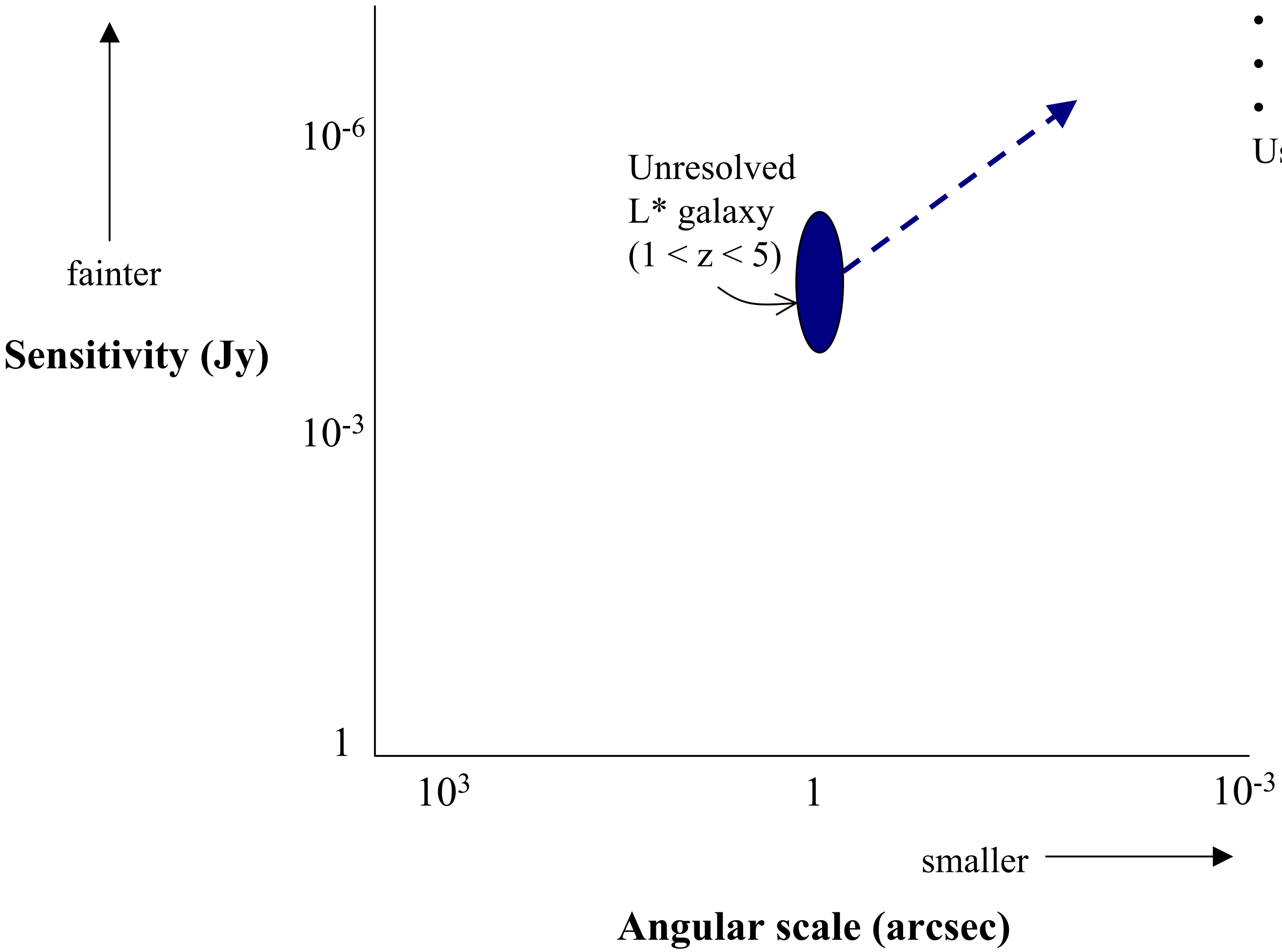


SPIRIT and SPECS Science Capabilities and Mission Concepts

Space-based far IR/submillimeter interferometry is needed to learn how stars and planetary systems form and to answer fundamental questions concerning the development of structure in the universe. I will describe concepts for the Space Infrared Interferometric Telescope (SPIRIT) and the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS). Both are imaging and spectral Michelson interferometers operating in the wavelength range ~40 - 800 microns. SPIRIT, which could be launched in a decade, is built on a deployable boom and has a maximum baseline of ~30 - 50 m, providing sub-arcsecond resolution in the far-IR. This NASA Origins Probe candidate will image extrasolar debris disks and protostars in the far-IR, where their brightness peaks, and it will beat extragalactic source confusion and provide the continuum and line spectra of galaxies out to high redshifts. SPECS, a NASA Vision Mission, uses formation flying to attain baseline lengths up to 1 km, and thus angular resolution comparable to that of the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST), and the Atacama Large Millimeter Array (ALMA). SPIRIT and SPECS will provide access to many important cooling and diagnostic spectral lines and to the bulk of the thermal emission from dust, and make observations complementary to those obtainable with ALMA, SAFIR, and JWST.



The Sensitivity - Angular Resolution Phase Space



Show:
- L* galaxy as function of z
- Low-mass protostar
- Debris disk

Use dashed line where source is unresolved, show decreasing flux p resel where source is resolved

SA

Hersch

Spitzer

COBE

IRAS